

Review

Organic Pollutant Degradation Through Photocatalysis: Progress, Challenges, and Sustainable Solutions (Mini Review)

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Abstract

The rapid increase in global population and industrial activities has intensified the discharge of toxic organic pollutants—including antibiotics, dyes, phenolic compounds, and pesticides—into the environment, posing critical threats to both ecosystems and human health. Conventional treatment technologies remain largely inadequate for their complete removal, particularly for pollutants with complex structures and high persistence. Among advanced approaches, photocatalytic systems have emerged as a sustainable and environmentally friendly technology, capable of mineralizing organic pollutants into harmless end products. However, their large-scale application is hindered by inherent limitations such as restricted visible-light activity, low quantum efficiency, and rapid recombination of charge carriers. This mini-review critically examines recent advances aimed at overcoming these bottlenecks, including band gap engineering, metal and non-metal doping, and the incorporation of carbon-based nanomaterials (e.g., CNTs, GO, CQDs). Special emphasis is placed on strategies that enhance photocatalytic activity under visible light, as well as the emerging potential of waste-derived carbon-based photocatalysts for sustainable applications. Finally, key research gaps—such as scalability, long-term stability, and techno-economic feasibility—are discussed to provide future perspectives on the rational design of next-generation photocatalysts.

Keywords: photocatalytic systems; organic pollutants; photocatalysts; carbon-based materials; purification technologies

1. Introduction

In recent years, the increasing complexity of emerging organic pollutants and the limitations of conventional treatment technologies have intensified the global focus on photocatalytic remediation. Since the pioneering Honda–Fujishima report in 1972, photocatalysis has been widely recognized as a promising strategy for environmental purification, owing to its ability to activate redox reactions under light irradiation. However, achieving high photocatalytic efficiency requires the simultaneous optimization of light absorption, charge separation, and surface reaction kinetics. This mini-review evaluates recent developments in band gap engineering, doping strategies, and carbon-based hybrid materials, with emphasis on next-generation photocatalysts capable of functioning efficiently under visible-light irradiation.

The continuous growth of the global population and rapid industrialization have significantly intensified the release of hazardous pollutants into the environment. Among these, organic contaminants such as dyes, antibiotics, phenolic derivatives, and pesticides



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are of particular concern due to their high toxicity, persistence, and complex molecular structures, which render them resistant to natural biodegradation. Their long-term accumulation in aquatic ecosystems not only disrupts ecological balance but also poses severe and long-lasting risks to human health [1].

A variety of conventional treatment technologies—including adsorption, coagulation–flocculation, membrane filtration, and biological processes—have been widely applied to address these pollutants. While effective to some extent, these methods generally suffer from critical drawbacks: they often fail to achieve complete mineralization, may generate secondary waste streams, and exhibit reduced efficiency when confronted with high pollutant concentrations or structurally stable compounds [2]. These limitations underscore the urgent need for advanced treatment strategies capable of ensuring sustainable and complete removal of organic contaminants.

In this context, photocatalytic systems have emerged as one of the most promising solutions, owing to their ability to degrade a wide range of toxic organic pollutants under mild operating conditions while minimizing the formation of harmful byproducts. The performance of photocatalysis, however, is governed by multiple parameters, including solution pH, light intensity and wavelength, reaction temperature, and—most critically—the physicochemical nature of the photocatalyst. Metal oxide semiconductors such as TiO_2 , ZnO , and SnO_2 have been extensively studied due to their low cost, tunable morphology, and chemical stability. Nevertheless, their real-world application is still constrained by poor visible-light absorption, low quantum efficiency, and rapid electron–hole recombination, which limit overall degradation efficiency [3].

To address these bottlenecks, recent research has focused on band gap engineering, metal and non-metal doping, and the integration of carbon-based nanomaterials (e.g., graphene oxide, carbon nanotubes, and carbon quantum dots). These strategies have demonstrated significant improvements in light absorption, charge separation, and catalytic stability, thereby expanding the practical potential of photocatalytic systems for water purification.

This mini-review provides a critical evaluation of these recent advances, highlighting their role in improving photocatalytic efficiency for organic pollutant removal. In addition, it identifies key research gaps—including challenges of scalability, catalyst stability, and long-term reusability—and outlines future perspectives toward the rational design of sustainable next-generation photocatalysts.

1.1. Organic Pollutant Types

Organic pollutants represent a diverse group of compounds that are typically resistant to biodegradation and have severe ecological and human health implications. These substances originate from multiple anthropogenic sources and contaminate water, soil, and air, resulting in long-term environmental persistence. The most widespread categories include dyes, antibiotics, phenolic compounds, pesticides, detergent residues, and petroleum derivatives. Their removal from aquatic systems is particularly challenging due to their structural complexity and stability.

Dyes: Synthetic dyes are extensively used in industries such as textiles, paper, plastics, rubber, cosmetics, paints, and leather. More than 10,000 commercial dyes are currently in use worldwide. Their low cost and high stability have made them indispensable to modern manufacturing, but these same properties hinder their degradation in the environment. Wastewater effluents containing dyes not only impart color but also introduce toxic and carcinogenic compounds, raising serious environmental and public health concerns [3,4].

Antibiotics: The global consumption of antibiotics has dramatically increased in the last two decades, with projections suggesting a 67% rise by 2030, particularly in countries with high population density and intensive livestock production [5–7]. The accumulation of antibiotic residues in wastewater contributes to the spread of antibiotic-resistant bacteria and resistance genes, representing one of the most pressing global health threats [8]. Their persistence and potential to bioaccumulate make them especially difficult to manage with conventional treatment technologies.

Phenolic Compounds: Phenolic derivatives, commonly released from petrochemical, plastics, pesticide, and resin industries, are toxic even at trace levels and significantly alter the taste and odor of water [9]. Their stability and solubility facilitate rapid dispersion into aquatic ecosystems, where they disrupt microbial communities and pose long-term risks to both aquatic and terrestrial organisms.

Pesticides: Widely applied in agriculture to increase yields, pesticides remain a leading source of organic contamination in soil and water. Their high toxicity, coupled with extensive application, results in environmental persistence and bioaccumulation. Runoff, spray drift, and volatilization further facilitate their widespread distribution, exposing non-target organisms and humans alike. Many pesticides act as endocrine disruptors and carcinogens, which amplifies public concern regarding their environmental and health impacts [10,11].

Overall, these groups of pollutants are highly resistant to conventional treatment technologies and demand the development of advanced methods, such as photocatalytic systems, to ensure their effective removal and mitigate their long-term ecological impact.

1.2. Methods Used in Organic Pollutant Removal

Emerging technologies continue to advance strategies for the removal of organic pollutants, with the ultimate goal of achieving safe and sustainable water quality [12,13]. Conventional and modern approaches are broadly classified into physical, chemical, and biological processes [14]. Each category provides distinct advantages; however, most conventional treatments are insufficient for the complete mineralization of persistent organic pollutants, necessitating the exploration of advanced alternatives.

1.2.1. Physical Treatment Methods

Physical processes rely predominantly on mechanical separation principles and do not involve chemical transformation of pollutants. The most widely applied methods are adsorption and membrane filtration, both of which have been extensively studied for wastewater remediation [15].

Adsorption: Adsorption has emerged as one of the most practical and widely applied methods for pollutant removal due to its simplicity, low operational cost, and high efficiency [16]. Pollutant molecules adhere to the surface of adsorbents through π - π interactions, electrostatic forces, van der Waals interactions, and hydrophobic effects. Activated carbon, zeolites, and ion-exchange resins are the most commonly used adsorbents. While adsorption demonstrates high removal efficiency for a wide range of organic and inorganic pollutants, its performance is often limited by competitive adsorption, surface fouling, and high regeneration costs [17–19]. Furthermore, adsorption typically transfers contaminants from water to a solid phase rather than degrading them, thereby creating challenges for long-term sustainability. A comparative overview of adsorption capacities reported for various adsorbents is presented in Table 1.

Table 1. Organic Pollutant Removal Performance of Zeolite and Other Adsorbents.

Reference	Adsorbent Used	Experimental Conditions	Pollutant	Removal Efficiency	Results
[20]	Zeolite	Pol. Con: 5–50 mg/L Adsorbent: 0.1–1.2 g pH: 3	Dichlorodiphenyl trichloroethane (DDT)	30%	As pH increased, adsorption efficiency decreased; the highest efficiency was observed at pH 3 (acidic conditions). Increased zeolite amount improved adsorption.
[21]	Sewage Sludge	Pol. Con: 50–800 mg/L Adsorbent: 20 mg pH: 7	Tetracycline	286.913 mg/g	High performance due to strong π – π interactions and penetration into porous structure.
[22]	Y-Type Silica Zeolites	Pol. Con: 0–50 μ mol/L Adsorbent: 30 mg	Trichloroethylene	1600 μ mol/g	Low adsorption affinity at low concentrations; capacity increased rapidly at higher concentrations due to π – π interactions between TCP molecules.
[23]	Activated Carbon	Pol. Con: 100–150 mg/L Adsorbent: 0.01–0.06 g, pH: 2.1	Sulfamerazine	165.67 mg/g	Maximum adsorption was observed at pH 2.1 and with 0.6 g/L of activated carbon.

All performance values (removal efficiency, adsorption capacity, degradation rate) are presented as originally reported in the cited studies to avoid misinterpretation arising from conversion between different experimental conditions.

Membrane Filtration: Membrane separation relies on semi-permeable barriers that selectively retain pollutants based on molecular size, charge, and solubility [24]. Depending on pore size, membrane processes can be classified into microfiltration, ultrafiltration, nanofiltration, and reverse osmosis [25]. These methods provide high selectivity and can effectively remove dyes, pharmaceutical residues, and other emerging contaminants. However, significant drawbacks remain, including high energy consumption, membrane fouling, limited chemical stability, and high production costs [18,19]. The development of thermally stable and reusable membranes is therefore a critical research direction. Overall, while adsorption and membrane filtration are indispensable in water treatment, their limitations in terms of regeneration, cost, and lack of complete degradation underscore the need for advanced oxidation and photocatalytic systems, which can achieve mineralization rather than mere separation. Table 2 presents a comparison of ceramic, nanofiltration, and cement-based membranes under varying operating conditions.

Table 2. Removal Efficiency of Different Membrane Types Against Pollutants in Industrial Wastewater.

Reference	Membrane Type Used	Target Pollutant	Experimental Conditions	Removal Efficiency	Results
[26]	Ceramic Membrane	Raw wastewater from the dairy industry, pulp & paper industry, and biomass gasification plant	Temperature: 30 °C Stirring Speed: 120 rpm Pol. Con: Dairy: 2234 mg/L Pulp & Paper: 937 mg/L Biomass: 2157 mg/L Pressure: 34–172 kPa	Dairy: 56.3% Pulp&Paper: 47.3% Biomass: 64.8%	The low-cost ceramic microfiltration membrane effectively removed bacterial biomass after biodegradation, significantly improving COD removal in wastewater.
[27]	Zeolite-incorporated Thin Film Nanocomposite (TFN-1500) Nanofiltration Membrane	MgSO ₄ , NaCl, 21 different pharmaceutical compounds	Temperature: 25 °C Pressure: 150 psi pH: 7.1 NaCl, MgSO ₄ : 2000 mg/L Pharmaceuticals: 20 μ g/L	MgSO ₄ : 93.4% NaCl: 27.7% Pharmaceuticals (PhACs): >90%	The TFN-I nanocomposite nanofiltration membrane developed in this study showed high permeability and good pollutant removal due to the zeolite nanoparticle incorporation.

Table 2. Cont.

Reference	Membrane Type Used	Target Pollutant	Experimental Conditions	Removal Efficiency	Results
[28]	Cement-based Microfiltration Membrane	Nitrobenzene, BP-4, p-CP(p-chlorophenol), p-CNB, p-CBA, p-CA	Pol. Con: 0.064 mM Duration: 30 min pH: 6.7 Pressure: 1.12–12.48 MPa	99%	The cement-free, low-cost microfiltration membrane showed excellent pollutant retention thanks to its porous structure, achieving high removal when combined with ozone and maintaining performance upon reuse.

1.2.2. Chemical Treatment Methods

Chemical treatment approaches rely on the addition of reagents to oxidize, precipitate, or transform pollutants into less harmful forms [29]. Although these methods are effective in many contexts, they often generate secondary waste streams, require high chemical input, and involve costly operational and maintenance processes. Two widely studied subcategories are coagulation–flocculation and ion exchange. Detailed removal efficiencies obtained using FeCl_3 , PACl, and composite coagulant systems can be found in Table 3.

Table 3. Chemical Treatment Efficiency and Application Conditions According to Coagulant Types.

Reference	Coagulant Used	Pollutant	Experimental Conditions	Removal Efficiency	Results
[30]	Ferric Chloride (FeCl_3)	Dissolved Organic Carbon in Wastewater	pH: 5.4–7.6 Pol. Con: 13.6 mg/L Zeta Pot: +6.9 to −14 mV	45%	Highest efficiency was achieved at pH 5.5.
[31]	PACl (Polyaluminum Chloride)	CuO Nanoparticles	pH: 3–8 Pol. Con: 10 mg/L Coag: 200 rpm, 2 min Floc.: 20 rpm, 20 min Settling: 30 min Zeta Pot: 32.1 to 0.9 mV	>95%	Hydrophobic organics hinder particle aggregation, requiring higher doses, while hydrophilic substances allow high removal with lower coagulant doses.
[32]	PACl+ Diatomite	Oily Wastewater	pH: 7–10 Coag: 200 rpm, 2 min Floc: 50 rpm, 20 min Settling: 60 min	73.6%	Diatomite addition enabled high efficiency at low coagulant dosages. pH had no significant effect on removal efficiency.
[33]	PACl/PAM (Polyacrylamide) + NaClO	Dimethyl Disulfide Dimethyl Trisulfide Diethyl Disulfide Diethyl Trisulfide	pH: 5.8–8.2 Pol. Con: 100 mg/L	98%	The combination of PACl/PAM and NaClO showed high removal efficiency (98%) for thioethers and effectively reduced turbidity.

Coagulation and Flocculation: This process remains one of the most commonly used chemical treatments due to its simplicity, cost-effectiveness, and ability to remove colloidal particles. Coagulants such as ferric chloride (FeCl_3) or polyaluminum chloride (PACl) destabilize suspended solids, enabling their aggregation into larger flocs that can be separated through sedimentation [16]. While high removal efficiencies are often reported (Table 3), performance is strongly influenced by pH, zeta potential, and the nature of pollutants. For example, oily wastewater or hydrophobic organics frequently require higher coagulant doses to achieve efficient removal. Despite its effectiveness, coagulation–flocculation generates significant amounts of chemical sludge that require further treatment or safe disposal, raising environmental and economic concerns.

Ion Exchange: Ion exchange resins operate on the principle of substituting dissolved ions in solution with ions of similar charge bound to a solid matrix [34]. Advances in resin synthesis have led to tailored structures with high ion-exchange capacities and improved selectivity [35,36]. As illustrated in Table 4, magnetic ion exchange (MIEX) resins exhibit strong potential for antibiotic removal, while porous Fe₂O₃ microcubes show promise for both heavy metals and organics. However, resins must be periodically regenerated, often using concentrated chemical solutions, which increases cost and results in secondary brine waste [37].

Table 4. Removal Capacities of Ion Exchange Resins According to Pollutant Types.

Reference	Resin Used	Pollutant	Experimental Conditions	Removal Capacity	Results
[38]	Porous Fe ₂ O ₃ Microcubes	Cr(VI)	pH: 5 Temp: 298–328 K Duration: 24 h Pol Con: 10–80 mg/L	175.5 mg/g	This study shows that low-cost, high surface area porous Fe ₂ O ₃ microcubes (P-Fe ₂ O ₃) are effective adsorbents for both heavy metals and organic pollutants.
[39]	Magnetic Ion Exchange Resin	Sulfamethoxazole Tetracycline Amoxicillin	pH: 3–11 Temp: 25 °C Duration: 30 min Pol. Con: 20–5000 g/L	789. µg/mL 443.2 µg/mL 155.2 µg/mL	With high adsorption capacity and reusability, MIEX resin is a promising adsorbent for removing antibiotics from water.
[40]	Cation Exchange Resin	Ca, Fe, Sr	pH: 3 Temp: 21 °C Duration: 24 h	–	Neodymium (Nd) forms a stable complex with the resin through multiple phosphonate groups, enabling strong binding.

Although chemical treatment methods can achieve high pollutant removal efficiencies, their limitations—including sludge generation, high reagent consumption, and incomplete mineralization—reduce their sustainability for long-term wastewater management. As such, they are increasingly considered as pre-treatment or complementary methods that can be integrated with advanced oxidation or photocatalytic systems to achieve complete degradation and mineralization of persistent organic pollutants. Ion-exchange resin capacities for different contaminant types are listed in Table 4.

1.2.3. Advanced Oxidation Processes (AOPs)

Advanced Oxidation Processes (AOPs) have become a cornerstone in modern wastewater treatment due to their ability to degrade pollutants that are persistent and resistant to conventional treatment methods. Unlike physical and chemical separation techniques, AOPs aim not only to remove but also to mineralize contaminants, transforming them into environmentally benign products such as CO₂, H₂O, and inorganic ions [15]. The hallmark of AOPs lies in the generation of highly reactive oxygen species (ROS), primarily hydroxyl radicals (•OH), which exhibit extremely high oxidation potential (2.80 V) and can attack a broad spectrum of organic pollutants non-selectively and at near diffusion-controlled rates [41,42].

The primary goal of AOPs is therefore the complete breakdown of complex organic molecules that are otherwise difficult to treat—such as pharmaceuticals, dyes, pesticides, and endocrine-disrupting compounds—into smaller, less toxic intermediates and eventually into mineralized products. However, the efficiency and practicality of these processes depend on both the oxidizing agents employed and the operational conditions under which radicals are generated. Among the most common AOP strategies are ozonation, Fenton-based processes, photocatalytic oxidation, and electrochemical oxidation [43–45]. Table 5 compares ozonation performance across various pollutants and operating conditions.

Ozone Oxidation: Ozone is a powerful oxidant capable of reacting with a variety of organic and inorganic contaminants across a wide pH range. Ozonation proceeds via two distinct pathways: (i) direct oxidation through molecular ozone, which is selective towards

electron-rich compounds (e.g., phenols, olefins), and (ii) indirect oxidation through the decomposition of ozone into hydroxyl radicals, which provides a broader, non-selective attack on pollutants [46].

While effective, ozonation faces persistent limitations. A major challenge is the low utilization efficiency of ozone, since a large fraction of generated ozone decomposes before interacting with target pollutants. Moreover, ozonation processes often require high energy input to generate sufficient ozone concentrations, and their performance is sometimes unstable due to fluctuations in wastewater composition [47]. Although ozone treatment does not typically produce harmful sludge, incomplete oxidation may generate toxic byproducts, such as aldehydes and carboxylic acids, which necessitate further treatment. Therefore, research has increasingly focused on catalytic ozonation (e.g., metal oxides, activated carbon, natural minerals) to enhance radical production, improve selectivity, and lower energy costs.

Table 5. Removal Efficiency of Ozone and Fenton-Based Advanced Oxidation Methods.

Reference	Method Used	Target Pollutant	Experimental Conditions	Removal Efficiency
[48]	Ozone Oxidation	17 α -ethinylestradiol	pH: 8 Pol. Con: 60–300 μ g/L	90%
[49]	Ozone Oxidation	Reactive Black 5	Pol. Con: 5.26 mg/L Duration: 5 min	75%
[50]	Catalytic Ozonation (with Iron Filings)	Biologically Treated Textile Wastewater	pH: 7.37–7.84 Pol. Con: 142 mg/L	51%
[51]	Ozonation and Adsorption	Reactive Red Textile Dye	Pol. Con: 150 mg/L	37%

Fenton Oxidation: The Fenton process is one of the most established AOPs, involving the reaction of hydrogen peroxide (H_2O_2) with ferrous ions (Fe^{2+}) under acidic conditions to generate hydroxyl radicals [52,53]. Its strengths include simple reaction conditions, low cost of reagents, and high efficiency in degrading a wide range of pollutants such as dyes, phenols, and pharmaceuticals. Fenton chemistry has been widely applied in treating industrial effluents, particularly from textile, cosmetic, and pharmaceutical sectors.

Despite its advantages, two key drawbacks limit its full-scale application: (i) the continuous consumption of iron salts, which results in high operational costs, and (ii) the generation of large quantities of iron-rich sludge, which requires disposal or secondary treatment, thereby creating an additional environmental burden [54]. To mitigate these issues, Photo-Fenton and Electro-Fenton processes have been developed. Photo-Fenton reactions, enhanced by UV or solar irradiation, promote the photoreduction of Fe^{3+} to Fe^{2+} , sustaining radical production and improving mineralization efficiency. While these modifications increase performance, they also raise questions of economic feasibility, energy requirements, and practical scalability. The efficiency of Fenton and photo-Fenton processes for different pollutants is presented in Table 6.

Table 6. Removal Efficiency of Fenton-Based Advanced Oxidation Methods.

Reference	Method Used	Pollutant	Experimental Conditions	Removal Efficiency	Results
[55]	Fenton Process	Reactive Orange 16	Pol. Con: 100 mg/L	97%	The Fenton process is technically simple and has low environmental costs, making it an effective alternative for textile wastewater treatment in developing economies.
[56]	Fenton Process	Textile Dyes	Pol. Con: 1250 mg/L pH: 3 Duration: 0–30 min	90%	Fenton oxidation achieved complete color removal and reduced COD to 110–130 mg/L, outperforming biological treatment for textile wastewater.

Table 6. Cont.

Reference	Method Used	Pollutant	Experimental Conditions	Removal Efficiency	Results
[57]	Photo-Fenton	Cosmetic Wastewater	pH: 3 Duration: 40 min Pol. Con: 6968 mg/L	95%	COD values before and after oxidation showed complete removal of organic compounds during dye removal from cosmetic wastewater.
[58]	Photo-Fenton	Diclofenac	pH: 2.87 Duration: 101 min Pol. Con: 9350 mg/L	99%	Complete degradation of diclofenac suggests that other pharmaceuticals with similar structures can also be removed using photo-Fenton oxidation.

Electrochemical Oxidation: Electrochemical oxidation is a versatile AOP that exploits electrode reactions to oxidize pollutants either directly at the electrode surface or indirectly through the electrogeneration of oxidizing species such as $\bullet\text{OH}$, O_3 , or active chlorine species [52]. The process is subdivided into:

- **Direct EO:** in which hydroxyl radicals generated at the anode attack pollutants adsorbed onto the electrode surface, leading to their degradation.
- **Indirect EO:** where electrogenerated oxidants (e.g., O_3 , H_2O_2 , Cl_2) diffuse into the bulk solution to degrade contaminants.

Recent studies highlight the exceptional efficiency of boron-doped diamond (BDD) electrodes, which possess high oxygen overpotential and enable the formation of physisorbed hydroxyl radicals with strong oxidizing potential [59–61]. BDD-based EO has demonstrated near-complete mineralization of persistent pollutants such as perfluoroalkyl substances (PFAS), pharmaceuticals, and textile dyes. Compared with conventional electrodes (Ti/RuO_2 , Ti/IrO_2), BDD exhibits superior stability and degradation efficiency. Nonetheless, EO faces challenges of high capital cost, electrode fouling, and limited long-term durability, all of which constrain its large-scale deployment.

AOPs have revolutionized the treatment of recalcitrant organic pollutants by enabling their oxidative mineralization rather than simple separation. However, the application of AOPs at an industrial scale is often hindered by:

- High energy demands (ozone, EO).
- Secondary waste generation (Fenton sludge, chlorinated byproducts).
- Operational limitations (pH dependency, reagent consumption, catalyst deactivation).

For these reasons, AOPs are rarely sufficient as stand-alone technologies. Instead, they are increasingly deployed in hybrid treatment trains, where they serve either as a pre-treatment step (to break down complex pollutants into more biodegradable intermediates) or as a polishing step (to achieve complete mineralization after biological or physical treatment).

Notably, photocatalytic oxidation—often considered a branch of AOPs—offers a pathway to overcome many of these drawbacks. Unlike conventional AOPs, photocatalysis can be powered by solar energy, minimizing energy costs and chemical input. Integrating photocatalysis with ozonation, Fenton, or electrochemical systems further enhances radical generation, improves degradation rates, and reduces byproduct formation. Thus, the development of photocatalytic–AOP hybrid systems represents one of the most promising directions for the future of sustainable wastewater treatment. Electrochemical oxidation results using different electrode systems are summarized in Table 7.

Table 7. Removal Efficiency of Electrochemical-Based Advanced Oxidation Methods.

Reference	Electrodes Used	Pollutant	Experimental Conditions	Removal Efficiency	Results
[59]	Boron-Doped Diamond (anode) and Titanium (cathode) Electrodes	Perfluorooctanoic Acid (PFOA) Perfluorohexane Sulfonate (PFHxS) Perfluorooctanesulfonate (PFOS)	pH: 7 Duration: 2.5 h Electrolyte: 10 mM Na ₂ SO ₄ + 2 mM NaCl	PFOA: 94.0% PFHxS: 88.1% PFOS: 89.1%	The EO system developed with BDD and Ti electrodes provided high PFAS removal efficiency and low energy consumption, making it an effective treatment method.
[60]	Boron-Doped Diamond Electrode	Anastrozole	pH: 3–10 Pol. Con: 0.5–2 mg/L Duration: 90 min Electrolyte: 0.1 M Na ₂ SO ₄ & 0.1 M NaCl	82.4%	Electrochemical oxidation of ANZ is promising due to its operation without added chemicals and wide operating conditions, making it more feasible in the long term.
[61]	BDD, Ti/RuO ₂ -TiO ₂ , Ti/IrO ₂ -Ta ₂ O ₅ , Ti/IrO ₂ -RuO ₂ , Ti/RuO ₂ /IrO ₂ -Pt	Textile Wastewater	pH: 9.6 Duration: 8 h Pol. Con: 1480 mg/L	BDD: 100% Ti/RuO ₂ -TiO ₂ : 61%	Compared to BDD, the tested Ti/MMO anodes showed lower organic load removal and mineralization rates during electrochemical oxidation of textile wastewater.

2. Photocatalytic Systems

Photocatalytic systems have emerged as a clean, sustainable, and environmentally friendly technology for the removal of persistent organic pollutants from water and wastewater [11]. Unlike conventional separation or oxidation processes, photocatalysis has the unique capability of achieving complete mineralization of contaminants without generating toxic byproducts, thus offering a green and cost-effective treatment option [16,53]. Their versatility lies in their ability to utilize a wide absorption spectrum, ranging from ultraviolet (UV) to visible (Vis) light, enabling the degradation of pollutants under natural solar irradiation.

At the heart of photocatalytic systems are semiconductor-based catalysts, most notably metal oxides such as TiO₂, ZnO, and SnO₂. A photocatalyst can be described as a semiconductor material that, when irradiated with photons of energy equal to or greater than its band gap, generates electron–hole pairs capable of driving redox reactions on its surface [11]. In essence, a photocatalyst acts as a light-activated catalyst: it absorbs light energy, elevates electrons from the valence band (VB) to the conduction band (CB), and facilitates subsequent reactions by transferring this energy to adsorbed substances.

The mechanism of photocatalysis involves several interconnected steps. First, photon absorption excites electrons (e[−]) from the VB to the CB, leaving behind positively charged holes (h⁺). These photogenerated charge carriers migrate to the semiconductor surface, where they participate in redox reactions. The holes (h⁺) oxidize adsorbed water or hydroxide ions to generate hydroxyl radicals (•OH), while the electrons (e[−]) reduce dissolved oxygen molecules to produce superoxide anions (O₂•[−]). Collectively, these reactive oxygen species (ROS) exhibit extremely high oxidation potential and can attack a wide variety of organic molecules, leading to their degradation into non-toxic end products [62].

However, the efficiency of photocatalytic systems is not solely determined by charge generation. One of the critical challenges is the recombination of electron–hole pairs, which significantly reduces quantum efficiency. Additionally, the limited visible-light absorption of most traditional photocatalysts (e.g., TiO₂ with a band gap of ~3.2 eV) restricts their practical application under natural solar conditions. Therefore, strategies such as band gap engineering, heterojunction formation, doping with metal or non-metal ions, and coupling with carbon-based nanomaterials (e.g., graphene oxide, carbon nanotubes, carbon quantum dots) have been extensively investigated to improve light absorption, enhance charge separation, and increase photocatalytic efficiency.

Figure 1 illustrates the fundamental steps of the photocatalytic mechanism on a semiconductor surface. When the incident photon energy exceeds the band gap (Step I), electrons in the valence band are photoexcited to the conduction band, leaving behind positively charged holes (Step II). The photogenerated charge carriers may undergo recombination (Step III), or they may migrate to the catalyst surface, where electrons participate in reduction reactions with dissolved oxygen species, forming reactive intermediates such as superoxide radicals (Step V). Simultaneously, holes drive oxidation reactions involving water molecules or hydroxide ions, leading to the formation of hydroxyl radicals (Step V). These reactive oxygen species subsequently attack and degrade organic pollutants adsorbed on the catalyst surface, ultimately yielding mineralized products (Step IV). The dashed line represents the charge separation region/recombination zone. This sequence of excitation, charge separation, redox reactions, and pollutant degradation constitutes the overall photocatalytic process.

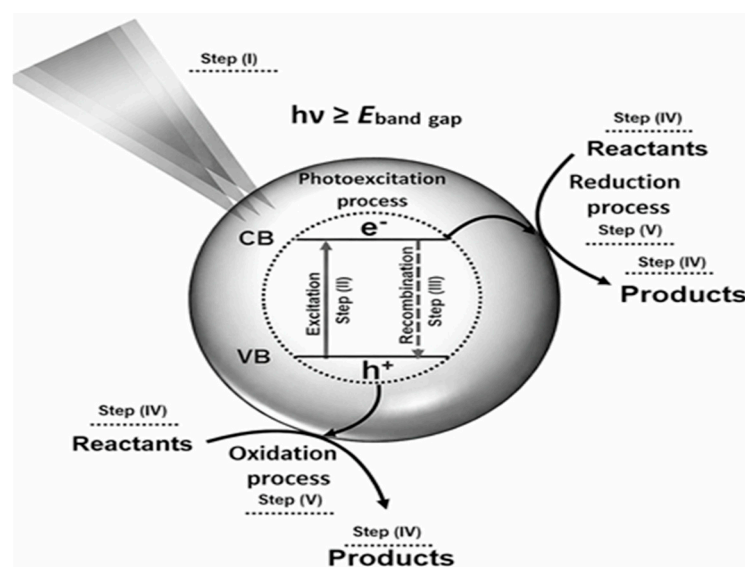


Figure 1. Schematic representation of the photocatalytic mechanism.

In summary, the photocatalytic process can be broken down into the following key steps [62]:

1. Absorption of incident photons by the semiconductor.
2. Excitation of charge carriers, with electrons promoted from the valence band to the conduction band.
3. Migration of photogenerated electrons and holes to the semiconductor surface.
4. Competition between recombination and surface reactions, where fast recombination reduces efficiency.
5. Redox reactions at the surface, wherein holes drive oxidation processes (e.g., $\bullet\text{OH}$ generation) and electrons facilitate reduction reactions (e.g., $\text{O}_2\bullet^-$ formation).

These interconnected processes determine the overall photocatalytic performance. Thus, the design of efficient photocatalytic systems requires not only a suitable semiconductor but also structural modifications and surface engineering to maximize charge utilization while minimizing recombination.

Photocatalytic degradation processes are strongly influenced by kinetic parameters, making kinetic modeling essential for translating laboratory results into scalable industrial systems. Most photocatalytic reactions follow pseudo-first-order kinetics based on the Langmuir–Hinshelwood (L–H) model, which describes the relationship between surface adsorption and reaction rate. However, deviations commonly occur in real wastewater

matrices due to competitive adsorption, mass-transfer limitations, and catalyst surface deactivation. Recent studies emphasize the importance of mechanistic kinetic modeling, incorporating factors such as photon flux, catalyst morphology, charge transfer efficiency, and reactive oxygen species (ROS) generation rates. Advanced modeling approaches—including computational fluid dynamics (CFD), artificial neural networks (ANN), and density functional theory (DFT)—are increasingly used to predict reaction pathways, optimize operating conditions, and guide photocatalyst design. Despite these efforts, challenges remain in establishing universal kinetic models that accurately capture complex heterogeneous reactions under variable light intensities and real-environment conditions.

2.1. Parameters Affecting Photocatalytic Systems

The efficiency of photocatalytic systems depends on a combination of operational and environmental parameters that control photon absorption, charge carrier dynamics, and pollutant–catalyst interactions. Key factors include light intensity and wavelength, solution pH, photocatalyst dosage, initial pollutant concentration, and reaction temperature. A detailed understanding of these parameters is critical for both laboratory optimization and large-scale implementation.

Effect of Light Intensity and Wavelength: The light source is the fundamental parameter driving photocatalytic degradation, as its photons provide the energy required to excite charge carriers within semiconductor materials. For a photocatalytic reaction to occur, incident photons must possess energy equal to or greater than the semiconductor's band gap, thereby promoting electrons from the valence band (VB) to the conduction band (CB) and leaving behind positively charged holes (h^+). These electron–hole pairs subsequently participate in redox reactions that generate reactive oxygen species (ROS), which are responsible for pollutant degradation [63].

Two aspects of the light source are particularly critical:

- **Light Intensity:** Higher light intensity increases the photon flux reaching the catalyst surface, resulting in greater electron–hole pair generation and enhanced ROS production. Consequently, pollutant degradation rates rise with irradiance. However, beyond an optimal threshold, excessive excitation can accelerate electron–hole recombination, leading to reduced quantum efficiency. Thus, optimization is required to balance ROS generation and recombination dynamics.
- **Light Wavelength:** The wavelength of the light determines whether photons can overcome the band gap energy of the catalyst. Conventional semiconductors such as TiO_2 are primarily UV-active, limiting their utilization under natural sunlight, where UV accounts for only ~5% of the spectrum. Visible-light-responsive photocatalysts (e.g., doped TiO_2 , $g\text{-C}_3\text{N}_4$, carbon-modified systems) are therefore essential to harness solar energy effectively and achieve practical large-scale applications.

Both intensity and wavelength govern photocatalytic activity, with optimal conditions requiring sufficient photon flux in the appropriate spectral range to maximize ROS formation while minimizing recombination losses.

The pH of the solution: The pH of the solution is a critical factor influencing photocatalytic degradation, as it directly governs both the surface charge of the photocatalyst and the ionic state of the pollutants [64]. The relationship between these two parameters determines adsorption, which is a prerequisite for efficient redox reactions on the catalyst surface.

- At low pH (acidic medium), photocatalyst surfaces generally acquire a positive charge, which enhances electrostatic attraction with anionic (negatively charged) pollutants such as azo dyes, leading to higher adsorption and improved degradation.

- At high pH (alkaline medium), surfaces tend to become negatively charged, favoring adsorption of cationic (positively charged) pollutants. In such cases, degradation is enhanced for compounds like methylene blue or rhodamine B.

The balance between the point of zero charge (pHpzc) of the catalyst and the pKa of the pollutant is therefore essential in optimizing photocatalytic performance. Moreover, pH can influence not only adsorption but also the efficiency of radical formation. For instance, in Fenton-assisted photocatalytic systems, acidic pH values promote hydroxyl radical generation, whereas strongly alkaline conditions may lead to scavenging effects that reduce efficiency.

In summary, pH acts as a double regulator: it dictates surface–pollutant interactions and modifies the reactivity of generated radicals. Thus, identifying the optimum pH for each catalyst–pollutant system is indispensable for achieving maximum photocatalytic activity.

Photocatalyst Amount: The dosage of photocatalyst is a crucial operational parameter that directly governs the efficiency of photocatalytic oxidation. Increasing catalyst loading enhances the number of active sites available for photon absorption and redox reactions, generally improving the degradation and mineralization of organic pollutants [65]. At optimum levels, higher surface area exposure facilitates faster charge carrier transfer and reactive oxygen species (ROS) formation, thus accelerating pollutant breakdown.

However, excessive catalyst loading introduces several negative effects. High particle density increases light scattering, reflection, and shielding, thereby preventing photons from penetrating into the bulk solution. Catalyst agglomeration at high concentrations also reduces the effective surface area and limits pollutant–catalyst interactions. Consequently, surplus catalyst can paradoxically lower the overall quantum efficiency of the system.

Therefore, each photocatalytic system requires an optimum catalyst dosage, which depends on the nature of the photocatalyst, pollutant type, and experimental conditions. Identifying this balance is essential to maximizing degradation efficiency while minimizing light losses and material waste. From an application standpoint, optimization of catalyst dosage is equally important for economic feasibility, as overuse not only reduces efficiency but also increases material and separation costs in large-scale water treatment.

Initial Concentration: The type and initial concentration of pollutants strongly influence the performance of photocatalytic systems. At low concentrations, sufficient photons and active sites are available to ensure efficient pollutant adsorption, charge transfer, and reactive oxygen species (ROS) attack, resulting in high degradation rates. However, as pollutant concentration increases, the efficiency of photodegradation typically declines [66].

This reduction arises from multiple factors:

- **Light attenuation:** High pollutant levels absorb and scatter incident photons, preventing adequate light penetration to the catalyst surface.
- **Active site saturation:** Excess pollutants compete for limited adsorption sites, restricting pollutant–catalyst interactions.
- **ROS scavenging:** Elevated pollutant concentrations increase the likelihood of ROS quenching before they can fully mineralize contaminants, reducing the net oxidation efficiency.

In practice, photocatalytic systems are often studied at pollutant concentrations ranging from micromoles ($\mu\text{mol}\cdot\text{L}^{-1}$) to millimoles ($\text{mmol}\cdot\text{L}^{-1}$) to maintain controlled degradation rates and to mimic realistic wastewater levels. For real effluents with much higher pollutant loads, pretreatment steps or catalyst modifications (e.g., higher surface area, heterojunctions, carbon supports) are typically necessary to sustain efficiency.

Thus, determining the optimum pollutant concentration range is critical to ensure reliable kinetics, minimize inhibitory effects, and facilitate the scalability of photocatalytic processes to industrial wastewater treatment.

Reaction Temperature: Reaction temperature is another parameter that significantly influences photocatalytic degradation efficiency. In general, a gradual increase in temperature enhances the kinetics of pollutant breakdown by accelerating diffusion rates, improving pollutant–catalyst interactions, and facilitating the generation of reactive oxygen species (ROS), particularly hydroxyl radicals ($\bullet\text{OH}$) [67]. Higher temperatures also reduce the likelihood of electron–hole recombination, thereby extending the lifetime of charge carriers and allowing more of them to participate in surface redox reactions. Collectively, these effects contribute to higher photocatalytic activity and faster mineralization of organic pollutants.

However, the effect of temperature is not unidirectional. While moderate heating improves reaction rates, excessive temperatures can be detrimental. Elevated thermal energy may destabilize the crystal structure of some photocatalysts, induce sintering or agglomeration of nanoparticles, and even promote side reactions that reduce selectivity. Furthermore, high-temperature operation increases energy demands, which undermines the economic and environmental advantages of photocatalysis in practical applications.

Thus, temperature acts as a double-edged parameter: controlled increases can enhance photocatalytic efficiency, but surpassing the optimal range can compromise both catalyst stability and process sustainability. Identifying and maintaining this optimum temperature window is essential for maximizing photocatalytic performance under real operating conditions.

2.2. Characteristics of Photocatalyst

The photocatalytic activity of a material is governed by several intrinsic properties, which collectively determine its efficiency and practical applicability. The most critical characteristics include band gap energy, band edge alignment with redox potentials, large specific surface area, uniform and controllable morphology, high chemical and thermal stability, and recyclability. An efficient photocatalyst must combine these features to ensure high pollutant degradation rates, long-term durability, and environmental safety.

Band Gap and Band Edge Position: The band gap defines the portion of the electromagnetic spectrum that can be absorbed by the photocatalyst. For solar-driven applications, semiconductors with band gaps within the visible region are desired, while suitable band edge positions relative to the $\text{H}_2\text{O}/\bullet\text{OH}$ and $\text{O}_2/\text{O}_2\bullet^-$ redox couples ensure effective radical generation.

Surface Area and Morphology: A large surface area and controlled nanostructure morphology increase the density of active sites, improve light absorption, and promote efficient adsorption of pollutants. Nanostructured morphologies (e.g., nanorods, nanosheets, mesoporous films) can further enhance charge separation and transport.

Chemical Stability and Reusability: Environmental applications demand materials that are chemically stable under varying pH, temperature, and ionic conditions. High reusability is also essential to reduce costs and prevent secondary waste generation.

Metal oxides such as TiO_2 , ZnO , SnO_2 , and Cu_2O possess these parameters to varying degrees and are therefore widely employed as photocatalysts [68]. Upon light irradiation, these semiconductors generate photocarriers (electrons and holes), which participate in surface redox reactions and enable pollutant degradation.

Titanium Dioxide (TiO_2): TiO_2 is the most extensively studied photocatalyst due to its high chemical stability, non-toxicity, low cost, and strong oxidizing power under UV light [69]. Its antimicrobial activity also broadens its environmental applications, including

air purification, self-cleaning surfaces, and water disinfection [70,71]. TiO_2 exists in three crystalline phases: anatase, rutile, and brookite. Among these, anatase typically exhibits higher photocatalytic activity, but studies have shown that a mixed anatase–rutile system (e.g., P25 TiO_2) achieves superior performance due to synergistic charge transfer between phases [72]. The primary limitation of TiO_2 is its wide band gap (~ 3.2 eV), which restricts activity to the UV region ($\sim 5\%$ of solar radiation), necessitating modifications (doping, heterojunctions, sensitization) for visible-light activation.

Zinc Oxide (ZnO): ZnO is another promising photocatalyst with properties similar to TiO_2 , including low cost, non-toxicity, environmental friendliness, and high redox potential [73–75]. It offers versatile functionality due to its wide band gap (~ 3.2 eV) and unique structural properties. ZnO has demonstrated high efficiency in degrading dyes, pharmaceuticals, and pesticides, with advantages in synthesis flexibility and complete mineralization potential [76]. However, ZnO suffers from photocorrosion under prolonged irradiation, which limits long-term stability. Research has therefore focused on surface modifications, dopants, and composite formation with carbon-based materials to enhance both durability and visible-light response.

Tin Dioxide (SnO_2): SnO_2 is a chemically stable, non-toxic, and low-cost semiconductor with excellent thermal stability, corrosion resistance, and optical transmittance ($>80\%$) in the visible region [77–79]. These characteristics make it attractive not only for photocatalysis but also for gas sensors, lithium-ion batteries, solar cells, and optoelectronic devices [80,81]. Despite its stability, SnO_2 has a relatively wide band gap (~ 3.6 eV), which limits visible-light absorption. Furthermore, its photocatalytic efficiency is often constrained by rapid electron–hole recombination. Strategies such as coupling SnO_2 with narrower band gap semiconductors, incorporating noble metals, or forming heterojunctions have been widely explored to improve its photocatalytic activity.

While TiO_2 , ZnO, and SnO_2 remain benchmark photocatalysts due to their stability, abundance, and environmental compatibility, each material faces inherent challenges such as limited visible-light absorption and charge recombination. Accordingly, recent research has shifted toward composite photocatalysts, doping strategies, and hybrid systems with carbon-based nanostructures to overcome these limitations. These approaches aim to enhance solar utilization, prolong charge carrier lifetimes, and ensure long-term reusability, thereby bringing photocatalysis closer to practical and scalable environmental applications. Table 8 provides a comparison of widely used metal oxide photocatalysts and their dye degradation performance.

Table 8. Photocatalytic Efficiency of Different Photocatalyst Materials Against Organic Dyes.

Reference	Photocatalyst	Pollutant	Experimental Conditions	Results
[82]	ZnO– TiO_2 nanoparticles	Methylene Blue	Duration: 180 min UV-A Light TiO_2 dose: 0.5–1.5 g/L	At 0.8 g/L TiO_2 dosage, 70% degradation of methylene blue was achieved.
[83]	$\text{SnO}_2/\text{TiO}_2$ nanoparticles	Methylene Blue Rhodamine B	Duration: 30–120 min UV-A Light	$\text{SnO}_2/\text{TiO}_2$ showed strong photocatalytic activity by completely degrading both dyes (100% removal for Rhodamine B and Methylene Blue).
[84]	ZnO/CuO	Methyl Orange	Duration: 180 min	The nanocomposite with a 3:1 ZnO/CuO ratio provided the best synergy and light absorption, achieving complete degradation of MO under UV.
[85]	TiO_2	Methylene Blue	Duration: 120 min UV-A Light	98% of methylene blue was removed under UV-A light.

3. Recent Advances in Photocatalytic Systems

Although traditional metal oxides such as ZnO, TiO₂, Fe₂O₃, and SnO₂ have demonstrated high efficiency in photocatalytic degradation of pollutants, their performance is often limited by insufficient charge carrier separation, rapid electron–hole recombination, and restricted visible-light utilization. These drawbacks reduce quantum efficiency and hinder large-scale applications. To address these challenges, recent research has focused on band gap modification, heterojunction engineering, and integration with carbon-based nanomaterials. Such strategies enhance light harvesting, improve charge carrier dynamics, and increase the durability of photocatalysts, thereby paving the way for more sustainable and scalable photocatalytic systems [86].

Heterojunction structures represent one of the most effective strategies for improving charge separation and extending the light absorption range of photocatalysts. In Type I heterojunctions, both electrons and holes migrate toward the semiconductor with a narrower band gap, whereas Type II heterojunctions promote spatial separation of charge carriers by allowing electrons and holes to transfer into different semiconductors [87]. More advanced configurations, such as Z-scheme and S-scheme heterojunctions, have gained significant attention due to their enhanced redox capability and internal electric field-driven charge separation [88,89]. Z-scheme systems emulate natural photosynthesis, retaining strong redox potentials, while S-scheme heterojunctions facilitate directional migration of electrons and holes, markedly improving visible-light photocatalytic activity [90]. These heterostructure strategies have become essential for designing high-performance photocatalysts capable of overcoming intrinsic recombination challenges [91]. Among the available modification strategies, S-scheme and Z-scheme heterojunctions have shown the most consistent visible-light performance enhancement owing to their directional charge migration and high redox retention [92]. In parallel, non-metal dopants such as nitrogen, sulfur, and phosphorus effectively narrow the band gap and promote visible-light harvesting, leading to more efficient ROS generation [93].

Recent studies have demonstrated that the construction of heterojunctions significantly enhances interfacial charge separation and visible-light utilization across a wide range of material systems. For instance, 2D–2D Bi₄O₅I₂/BiOBr:Yb³⁺,Er³⁺ Z-scheme heterojunctions exhibit excellent full-spectrum responsiveness and strong redox capability due to efficient upconversion and charge migration pathways [88]. Similarly, Z-scheme ZIF67/NiMoO₄ heterojunctions have been reported to achieve superior photocatalytic degradation of antibiotic pollutants through improved interfacial contact and reduced bandgap energy [89]. Furthermore, BiVO₄–Au–Cu₂O nanosheet systems with multiple charge transfer paths demonstrated remarkable photocatalytic efficiency under visible light due to plasmonic enhancement and ultrathin architectures [92].

In addition, Type-II heterojunctions such as P-doped g-C₃N₄/Rh-doped SrTiO₃ composites have shown effective charge separation and enhanced hydrogen evolution under visible-light irradiation [87]. Heterojunction-based photocatalysis has also been comprehensively reviewed for applications in nitrogen fixation, highlighting the crucial role of spatially separated charge carriers and band alignment in sustainable energy conversion processes [90]. Moreover, recent reviews have summarized g-C₃N₄/TiO₂-based heterojunctions as efficient photocatalysts for visible-light-driven degradation of organic pollutants, emphasizing the synergy between enhanced light absorption and reduced charge recombination [93]. Finally, plasmonic Z-type heterostructures such as TiN@(A,R)TiO₂ have further demonstrated how interfacial coupling and local surface plasmon resonance effects can synergistically improve visible-light photocatalytic efficiency [91].

Collectively, these findings confirm that heterojunction engineering—through careful band alignment, interface optimization, and dopant incorporation—remains a cornerstone

strategy for designing high-efficiency, visible-light-responsive photocatalysts capable of addressing modern energy and environmental challenges.

3.1. Material Modification by Metal and Nonmetallic Doping

Doping is one of the most effective approaches to tailor the electronic structure of photocatalysts. Incorporating metal or non-metal dopants introduces localized states within the band gap, reducing the excitation energy required for electron promotion and thus extending activity into the visible-light spectrum [94].

- **Metal Doping:** Transition metals such as Cu, Ag, and Pd have been widely used to improve redox properties and electron transfer efficiency. For example, Ag nanoparticles can act as electron sinks, suppressing recombination and enabling surface plasmon resonance (SPR) effects that enhance visible-light absorption [95]. Cu and Pd doping, on the other hand, can create additional trapping sites, improving charge separation and facilitating pollutant reduction reactions.
- **Non-Metal Doping:** Elements such as N, S, and C are frequently introduced to narrow the band gap and shift photocatalytic activity toward the visible region. Nitrogen doping, for instance, replaces lattice oxygen and introduces impurity levels close to the valence band, enhancing light absorption under solar irradiation.

Despite these advantages, excessive or poorly controlled doping can create recombination centers, leading to performance decline. Thus, optimizing dopant type, concentration, and synthesis method remains a critical research challenge. The influence of metal and non-metal dopants on photocatalytic performance is detailed in Table 9.

Table 9. Performance of Photocatalysts Modified by Metal and Nonmetallic Doping.

Reference	Photocatalyst	Pollutant	Experimental Conditions	Removal Efficiency	Results
[96]	Cu-Ni/TiO ₂	DIPA	Visible Light Band Gap: 2.2–2.8 eV	86.82%	Compared to pure TiO ₂ , the band gap decreased with Cu-Ni addition, resulting in significantly higher photocatalytic activity under visible light.
[97]	MnO-Zn/TiO ₂	Methylene Blue	Visible Light Band Gap: 2.66 eV Duration: 75 min	96%	Zn doping significantly improved efficiency and reduced the band gap.
[98]	0.25–1%Pd-TiO ₂	Methylene Blue	Visible Light Duration: 120 min	99.94%	The highest efficiency was achieved with 0.5% Pd content.

3.2. Carbon Nanotubes (CNTs)

Carbon nanotubes are highly attractive co-catalysts due to their one-dimensional structure, superior electron transport capacity, large surface area (150–1500 m²/g), and high mechanical and thermal stability [99,100]. Their conjugated π -electron system allows CNTs to act as efficient electron acceptors and shuttles, significantly reducing electron–hole recombination in semiconductor photocatalysts. Single-walled CNTs (SWCNTs) and multi-walled CNTs (MWCNTs) both provide high conductivity pathways, although their electronic properties vary with structural chirality and diameter. CNTs also enhance pollutant adsorption due to their high surface area and porous structure, which increases the contact between pollutants and catalytic active sites. When coupled with semiconductors such as TiO₂ or ZnO, CNTs form heterostructures that not only improve charge separation but also extend photocatalytic activity into the visible range. Nevertheless, challenges

remain regarding cost-effective synthesis, dispersion control, and environmental safety, which need to be addressed before large-scale deployment.

3.3. Graphene Oxide (GO)

Graphene oxide (GO) has emerged as a versatile additive for enhancing photocatalytic performance. Owing to its two-dimensional structure, large specific surface area, and abundant oxygen-containing functional groups, GO can strongly adsorb organic pollutants and provide additional active sites [96]. More importantly, GO functions as an efficient electron acceptor and transporter, facilitating charge separation and suppressing recombination when combined with semiconductor photocatalysts.

GO-based composites (e.g., TiO₂–GO, ZnO–GO) demonstrate superior performance in degrading dyes, pharmaceuticals, and pesticides under visible-light irradiation. The synergistic effect arises from the intimate interfacial contact between GO and the semiconductor, which promotes efficient charge transfer. However, excessive GO loading may hinder light absorption by shielding the semiconductor surface. Therefore, controlling the GO content and maintaining proper dispersion are crucial for optimizing photocatalytic efficiency. The visible-light photocatalytic activities of CNT-supported composite materials are listed in Table 10. The synergistic effects between GO and semiconductor photocatalysts are summarized in Table 11.

Table 10. Activities of Carbon Nanotube-Supported Composite Photocatalysts Under Visible Light.

Reference	Photocatalyst	Pollutant	Experimental Conditions	Removal Efficiency	Results
[101]	CNT-TiO ₂	Methylene Blue	Visible Light	83%	CNT-enhanced TiO ₂ activity under visible light, achieving moderate to high degradation efficiency.
[102]	ZnO-CNT	Methylene Blue	Visible Light	99%	The presence of CNT reduced the band gap, resulting in very high degradation efficiency.
[103]	CNT/TiO ₂ /ZnO	Rhodamine B	UV-A(3.0–3.2 eV)	90%	The ternary composite exhibited enhanced photocatalytic performance under UV by preventing electron-hole recombination.

Table 11. Activities of Graphene Oxide Supported Composite Photocatalysts Under Visible Light.

Reference	Photocatalyst	Pollutant	Experimental Conditions	Removal Efficiency	Results
[104]	ZnO/GO	Methylene Blue	Visible Light Band Gap: 2.5 eV	98.4%	The addition of GO reduced ZnO's band gap, enhanced activity under visible light, facilitated electron-hole separation, and accelerated degradation.
[105]	GO/TiO ₂	Methylene Blue	Visible Light	100%	GO enhanced the visible light activity of TiO ₂ , resulting in 100% removal efficiency.
[106]	GO/MnO ₂	Reactive Black 5	Visible Light Band Gap: 2.48 eV	70%	GO improved MnO ₂ performance by reducing charge carrier recombination, increasing radical generation, and enhancing photocatalytic activity.

3.4. Carbon Quantum Dots (CQDs)

Carbon quantum dots (CQDs) are quasi-spherical or semi-spherical carbon-based nanoparticles with diameters typically below 10 nm [107]. Their nanoscale size, quantum confinement effect, and abundant surface functional groups (e.g., hydroxyl, carboxyl, amino groups) endow them with unique optical, electronic, and chemical properties that are highly beneficial for photocatalytic applications [108].

One of the most important advantages of CQDs is their ability to act as both electron reservoirs and transport mediators. When integrated with semiconductor photocatalysts, CQDs facilitate efficient charge separation by capturing photogenerated electrons and shuttling them to the conduction band of adjacent materials. This reduces electron–hole recombination and prolongs charge carrier lifetimes, thereby enhancing overall photocatalytic activity. Additionally, CQDs possess strong up-conversion photoluminescence properties, enabling the absorption of longer-wavelength visible or near-infrared light and converting it into shorter-wavelength radiation capable of exciting wide-band-gap semiconductors. This significantly broadens the usable solar spectrum and improves photocatalytic efficiency under natural sunlight.

The high dispersibility and tunable surface chemistry of CQDs also promote strong interactions with pollutants, improving adsorption and reactivity. Moreover, CQDs are considered environmentally friendly due to their low toxicity, easy functionalization, and cost-effective synthesis routes from biomass and waste-derived carbon precursors.

Classification of CQDs based on structure (graphitic, amorphous, polymer-derived) and composition (pure carbon vs. heteroatom-doped, e.g., N, S, P, B) provides valuable insight into their photocatalytic behavior [109]. For instance, nitrogen-doped CQDs improve electron-donating capacity and enhance ROS generation, while sulfur- or phosphorus-doped CQDs shift optical absorption into the visible region. Such structural and compositional tailoring offers a theoretical and practical basis for designing next-generation photocatalysts with superior activity, stability, and sustainability. The photocatalytic activities of CQD-enhanced systems are provided in Table 12.

Table 12. Activities of Carbon Quantum Dots Supported Composite Photocatalysts Under Visible Light.

Reference	Photocatalyst	Pollutant	Experimental Conditions	Removal Efficiency	Results
[110]	ZnO ₂ /CQD	Tetracycline	Visible Light Band Gap: 2.93 eV	80%	Combination of CQDs with ZnO ₂ enhanced antibiotic degradation, achieving good efficiency under visible light.
[111]	CQD from Fish Scale Waste	Methylene Blue Reactive Red 120	Visible Light Band Gap: 2.95 eV Duration: 120 min	96.5% 97.8%	CQDs derived from biomass waste are both environmentally friendly and highly efficient in degradation.
[112]	Nitrogen-doped CQD	Methylene Blue Malachite Green	UV-A Duration: 120–180 min	97% 98%	N-doping increased radical generation in CQDs, resulting in high degradation efficiency for both dyes.

4. Conclusions

This mini-review distinguishes itself from earlier broad-scope photocatalysis studies by presenting an integrated perspective on the synergistic contributions of band gap engineering and carbon-based nanostructures, with particular emphasis on visible-light-driven and sustainable photocatalysts. The review highlights emerging materials—including carbon quantum dots, graphene oxide composites, MXene-based hybrids, and waste-derived carbon photocatalysts—and underscores their potential for enhancing charge separation, extending light absorption, and improving overall catalytic performance. Beyond summarizing laboratory-scale progress, the discussion addresses key challenges such as long-term stability, scalability, and environmental sustainability, offering a forward-looking framework for the rational design of next-generation photocatalysts.

Although conventional physical, chemical, and biological treatment methods can effectively remove low-toxicity or readily degradable pollutants, they remain insufficient

against highly toxic, persistent, and structurally complex organic contaminants. This limitation necessitates the development of advanced technologies capable of achieving complete mineralization rather than partial degradation. In this context, photocatalytic systems have received considerable attention for their ability to generate reactive oxygen species under light irradiation, converting hazardous pollutants into environmentally benign end products. Their efficiency is governed by multiple operational parameters, with catalyst type and composition playing the most decisive role.

Metal oxide semiconductors such as TiO_2 , ZnO , and SnO_2 are well-established photocatalysts due to their affordability, chemical stability, and morphological flexibility. However, their limited visible-light activity and high electron–hole recombination rates restrict their practical deployment. For these reasons, recent research has focused on band gap tuning, metal and non-metal doping, heterojunction construction, and integration with carbon-based nanomaterials, including CNTs, CQDs, and GO. These modification strategies significantly enhance visible-light utilization and charge carrier dynamics.

Despite these advances, long-term durability remains a persistent challenge for many photocatalytic systems. Although several studies demonstrate stability over 5–8 reuse cycles, only a few report sustained activity beyond 10 cycles. Photocatalysts based on robust heterojunctions, MXene composites, or carbon-supported structures exhibit the highest long-term stability due to enhanced charge mobility and reduced photocorrosion.

In addition to durability concerns, scaling photocatalysis from laboratory to industrial systems presents further obstacles. The major gaps include non-uniform photon distribution in large reactors, low photon utilization efficiency, difficulty in recovering fine photocatalyst particles, reduced activity in turbid wastewater streams, and the high energy cost associated with artificial irradiation. Furthermore, the long-term operational stability of catalyst coatings and fixed-bed systems also remains a critical bottleneck.

Environmental and safety considerations also play a role in practical implementation. Nanoparticle release during photocatalytic processes may pose risks such as bioaccumulation, oxidative stress, and potential toxicity to aquatic organisms. To minimize these concerns, recent research emphasizes immobilized photocatalyst films, magnetic photocatalysts enabling efficient post-treatment recovery, and membrane-supported systems that prevent nanoparticle leakage.

Performance in real wastewater matrices further highlights the complexity of practical applications. Photocatalytic efficiency typically decreases due to light scattering, competitive adsorption by natural organic matter, and the presence of inorganic ions such as Cl^- , HCO_3^- , and SO_4^{2-} . The most limiting deactivation mechanisms include surface fouling, metal ion deposition, catalyst passivation, and scavenging of reactive oxygen species. Carbon-based hybrids and S-scheme heterojunctions exhibit improved resistance to these matrix effects, yet optimization is still required.

Although technical performance metrics such as degradation efficiency, mineralization degree, and reusability are important for evaluating photocatalysts, sustainability assessment requires a broader perspective. Life Cycle Assessment (LCA) provides a systematic framework for quantifying the environmental impacts associated with photocatalyst synthesis, usage, regeneration, and end-of-life disposal. Recent LCA studies reveal that some photocatalysts with high laboratory-scale efficiency may impose significant environmental burdens due to energy-intensive synthesis routes, hazardous chemical usage, or low recyclability. Carbon-based photocatalysts derived from agricultural or industrial waste sources offer clear advantages by reducing raw material consumption and supporting circular economy principles. Additionally, the number of reuse cycles is a critical parameter in LCA, as improved durability reduces the overall environmental footprint. Therefore,

integrating LCA into photocatalyst development is essential for identifying sustainable pathways and guiding future materials design.

Looking ahead, the development of photocatalysts derived from renewable and waste-based carbon sources offers a promising direction for both environmental remediation and sustainable material design. Such approaches support circular economy principles while enabling low-cost, high-performance photocatalytic materials. Future research should prioritize scalable synthesis routes, real-environment durability, and mechanistic insights through advanced characterization and computational modeling, thereby bridging the gap between laboratory demonstrations and real-world applications.

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